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A Preliminary Urban Illumination Model

by Richard C. Shirkey

ARL-TR-4320 November 2007

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ARL-TR-4320 **November 2007**

A Preliminary Urban Illumination Model

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U.S. Army Research Laboratory

Computational and Information Sciences Directorate

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
November 2007	Final	

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER**
A Preliminary Urban Illumination Model	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Richard C. Shirkey	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
U.S. Army Research Laboratory Computational and Information Sciences Directorate Battlefield Environment Division (ATTN: AMSRD-ARL-CI-ED) White Sands Missile Range, NM 88002-5501	ARL-TR-4320
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
U.S. Army Research Laboratory 2800 Powder Mill Road Adelphi, MD 20783-1197	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)** ARL-TR-4320

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Army increasingly relies on night operations to accomplish its objectives. These night operations frequently require using night vision goggles and other light-sensitive devices, which are strongly affected by ambient lighting, a large component of which is urban. A preliminary urban illumination model is presented for use in tactical decision aids and wargames, which would allow for more accurate prediction of target acquisition ranges and increased realism in simulations. This initial model predicts broadband brightness as a function of population and distance (>10 km) from the city center under clear and overcast conditions. A technical overview of the model, along with future improvements, is presented.

15. SUBJECT TERMS

urban illumination, brightness distance relationship

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Richard C. Shirkey
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	SAR	28	**19b. TELEPHONE NUMBER** (*Include area code*)
U	U	U			(505) 678-5470

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Acknowledgements

The author would like to thank Dr. M.E. Cianciolo, The Analytic Sciences Corp., for providing much of the initial information and methodology used to construct this preliminary model.

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Summary

This preliminary urban illumination model is a parametric model that estimates city brightness as a function of distance, look-angle, and city population. Currently the model assumes a mostly clear atmosphere; it will be modified in the future to include other atmospheric aerosols. The underlying parametric model has been shown to reproduce the observed brightness values for a wide array of cities and geometries. The model consists of two major pieces: 1) estimating the overall broadband brightness due to the city and 2) breaking that broadband source term into its spectral components so that we can simulate the spectral radiance. The model also includes a rudimentary algorithm for determination of the amount of urban illumination scattered from various types of clouds under overcast conditions.

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1. Background

To predict the target acquisition range of a given sensor observing a specific target under specified weather conditions, one must know the sensor and target characteristics, the weather conditions, and the ambient illumination. The ambient illumination, which may be comprised of solar, lunar, galactic, and/or manmade lighting, strongly affects the ability of a sensor to "see" and, therefore, determine acquisition ranges. In nighttime warfare, frequently the brightest sources of illumination are either from the moon or from urban areas. For Soldiers and pilots using night vision goggles (NVGs), operating near urban areas, care must be taken to not saturate NVGs by looking directly at brightly lit areas and effectively blinding the wearer. For mission planning, training purposes, and estimates of target acquisition ranges, it is necessary to have a model that will accurately simulate all of the above lighting sources and be able to apply them to target acquisition problems such as ambient lighting conditions varying over the course of a mission. Unfortunately, different lighting exists in different cities around the world whose population, and therefore the amount of cultural lighting, varies significantly. Though models that consider such cultural variations do exist, they do not cover all of the above illumination sources and their computation time is too long for simulations that must run rapidly. This initial model balances runtime requirements against complexity and relies heavily on work carried out by the astronomical community and adaptations made by the Target Acquisition Weapons Software (TAWS) (*1*).

Calculating the illumination from distant city lights requires 1) modeling the illumination source intensity and spectra, or an equivalent database, and 2) solving complex radiative transfer calculations including multiple scattering and aerosol and molecular absorption in a non-homogeneous atmosphere. Currently a number of models exist for predicting urban illumination as a function of distance from urban centers at visual wavelengths or portions thereof. These models range from the empirical (*2–4*) and semi-empirical (*5–8*) to research grade (*9*) for the determination of brightness (direct + diffuse) of a city as seen by an observer through the atmosphere. These models were constructed primarily by members of the astronomical community to define the effects of light pollution on observatories and observation sites, resulting in the so-called brightness-distance relationship

$$B = CPD^{-\alpha}, \tag{1}$$

where B is the sky brightness, C and α are constants, P is the city population, and D is the distance from city center. This is the initial model chosen for implementation.

The second requirement necessary for the source model is an appropriate illumination database providing information about the lighting sources—their intensity and angular and spectral characteristics. The models previously mentioned use various illumination databases and, for the

most part, rely on population data to predict the urban illumination at remote locations. Cities frequently do not use the same type of lighting, leading to different city “spectral signatures,” and the type of lighting used is dependent upon differences in economic development and lighting practices (*6*). There are a number of different approaches that can be used to account for these variations. First, the overall broadband brightness due to the city may be estimated by, as was originally done by Walker (*2*, *3*), measuring the brightness in the astronomical V band (~0.48–0.62 μm) and then applying a population vs. intensity relation, to be discussed below. This method can be modified and improved by identifying the spectral composition of urban light and subsequently estimating the percentage that each light source contributes in a typical city and allocating the total brightness with these percentages.

A second, somewhat similar approach has been used by Aubé (*9*). He has acquired spectral data at various U.S. and Canadian locations, focused on key spectral lines representative of specific kinds of lighting (high pressure sodium, metal halide, and low pressure sodium). He then uses this data as input to his high-resolution research grade illumination model (the underlying model is a variant of Moderate Transmission (MODTRAN) (*10*)), using an iterative technique, comparing the model output to the observed data, to determine an effective aerosol optical depth that yields the observed sky brightness due to scattered light.

Recently, with the advent of digital satellite data, another approach may be viable. Using Defense Meteorological Satellite Program (DSMP) measurements coupled with Garstang’s illumination model (*8*), Cinzano, et al. (*11*), have produced a world atlas of artificial night sky brightness at sea level under clear skies. Making appropriate assumptions regarding the light distribution, it may be possible to use this atlas as an input source. This will be a source of future investigation for this work.

2. Introduction

Using the brightness-distance relationship, a version of an urban illumination model has been developed by astronomical researchers. The initial goal of this work was to develop a realistic yet simple model of urban illumination to add to the Infantry Warrior Simulation (IWARS) simulation. To that end, the mathematical rigor of certain parts of the approach was simplified with parametric relationships and approximations.

This preliminary parametric urban illumination model estimates city brightness as a function of distance, look-angle, and city population. It currently assumes a mostly clear atmosphere that will be modified in the future to include other atmospheric conditions (foggy, hazy, etc.) and is limited to distances in excess of 10 km from city center; this limitation will also be removed in future versions. The current model consists of two major pieces: 1) estimating the overall

broadband brightness due to the city and 2) breaking that broadband source term into its spectral components so that we can simulate the spectral radiance. Each of these pieces of the model is described briefly in section 3.

3. The Model

Garstang (*7*, *8*) developed a model to calculate the brightness as a function of distance, population, and zenith direction. It includes the effects of absorption, scattering, and direct attenuation. By running the complete model for varying input conditions for a small number of sample cities, he found that the illumination predicted by the model dropped off as in equation 1. This empirical relationship was shown to agree well with measurements taken earlier by Walker (*4*), who showed that the light intensity was proportional to $D^{-2.5}$. Since electromagnetic flux from quasi-point sources falls off as an inverse function of distance from the source, and the fact that atmospheric extinction also is a factor in flux reduction, an exponent of 2.5 is physically reasonable and also provides a check for the exponent α.

This brightness-distance relationship is valid for a zenith-pointing look-angle. To model directional dependencies for city light intensity, two corrections to the simple zenith brightness were made: 1) a Gaussian drop-off in intensity in the azimuthal direction and 2) a secant function for the zenith direction.

3.1 Model Details

3.1.1 Estimate Constants Used in Brightness-Distance Relationship

Garstang estimated the values of C and α and compared his results to a limited set of observations (*4*). These values were tabulated for a number of population categories and are reprinted here in table 1.

Using values taken from table 1, α and log C were then plotted and curve fit as a function of log P. Figures 1 and 2 show these plots along with the parametric curve used in the model for determination of α and C.

Table 1. Results compiled by Garstang (*7*) for the value of log C and α as a function of population for large distances.

log P	log C	α
3.0	-1.29	-1.90
3.5	-0.96	-2.19
4.0	-0.56	-2.48
4.5	-0.22	-2.69
5.0	0.22	-2.94
5.5	0.78	-3.23
6.0	1.91	-3.77
6.5	3.61	-4.50

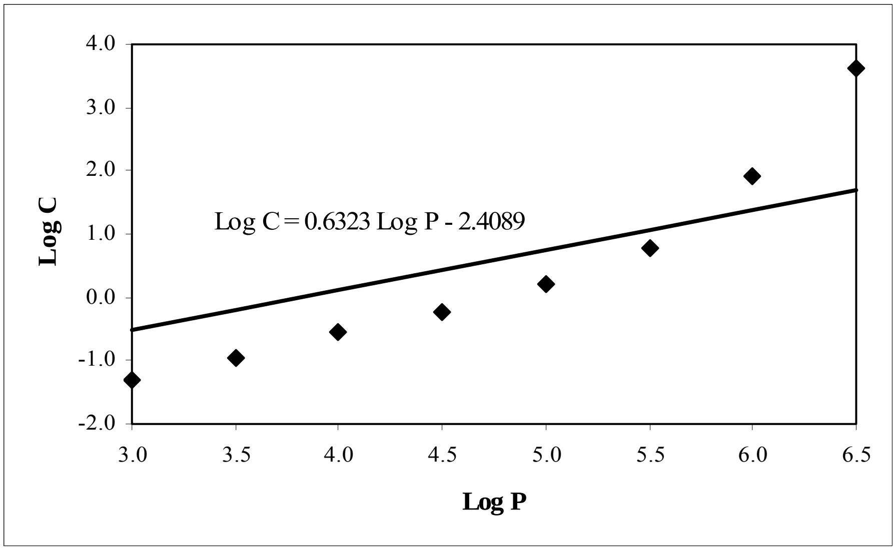

Figure 1. Relationship between log C and log P used in the brightness-distance relationship $B=CPD^{-\alpha}$; the diamonds are Garstang's estimates of log C and the solid line shows a linear fit to those points.

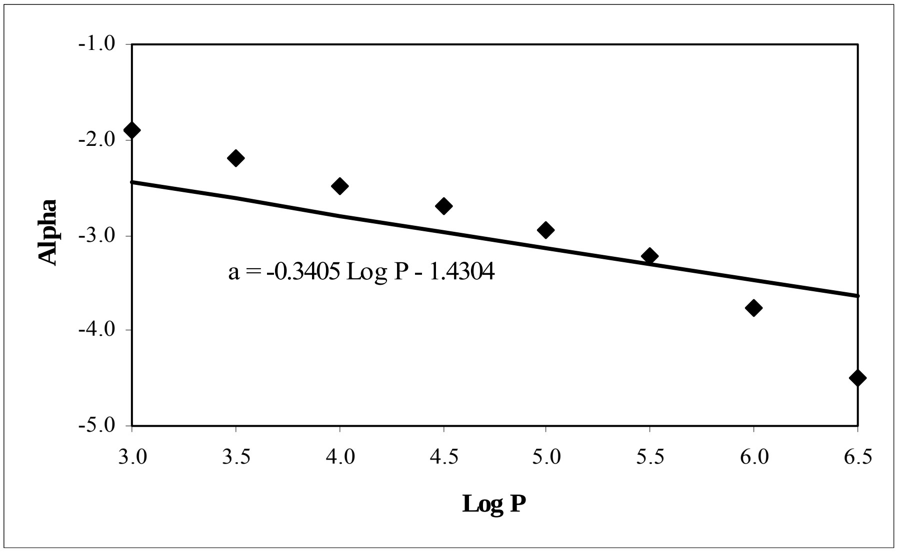

Figure 2. Relationship between α and log P used in the brightness-distance relationship $B=CPD^{-\alpha}$; the diamonds are Garstang's estimates of α and the solid line shows a linear fit to those points.

3.1.2 Zenith-Angle Effects

The brightness-distance relationship does not include a model for the angular effects on observed brightness. It is used to compute brightness in the zenith direction (i.e., looking straight up) only. To correct this, the effects of off-angle views and the corresponding corrections to the zenith brightness were made.

Berry (*12*) points out that, to a first approximation, we can assume that light originating from a city is scattered through an optically thin uniform layer of the atmosphere. The brightness of the layer is then proportional to a line-of-sight (LOS) thickness through the scattering layer. The LOS through a layer is proportional to the secant of the zenith angle; therefore, city lights, when viewed from far away, would appear to increase in brightness as the secant of the zenith angle.

To emulate this, a function was introduced to correct the zenith brightness for variations in zenith angle:

$$f(z) = A \sec(z), \qquad (2)$$

where A is a constant of proportionality determined from empirical data and z is the zenith angle in degrees.

Using data from Berry (*12*), Walker (*3*), and Garstang (*7*), the brightness for various cities was plotted as a function of zenith angle. These plots are shown in figure 3, plots (a) through (e). For each of the cities, a best-fit secant function with its corresponding constant of proportionality, A, was determined.

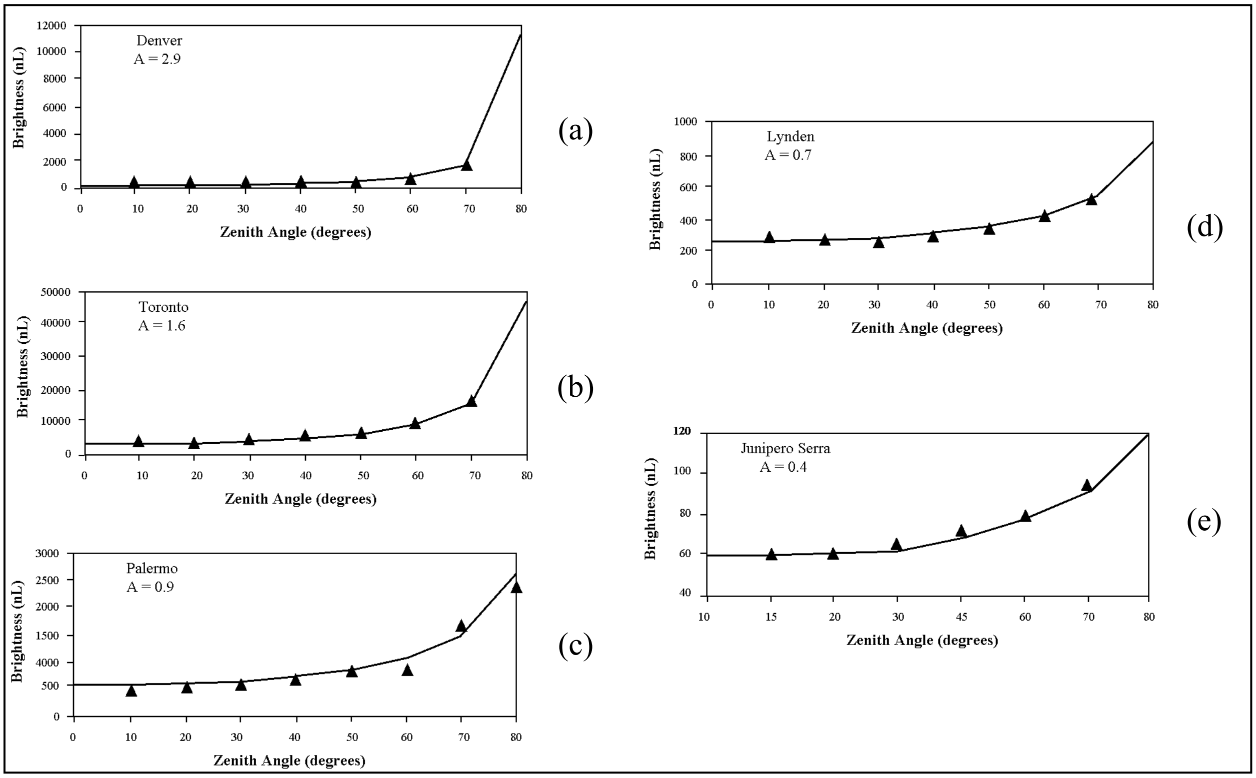

Figure 3. Plots of the brightness verses zenith angle showing the validity of the secant law: (a) Denver, A=2.9; (b) Toronto, A= 1.6; (c) Palermo, A=0.9; (d) Lynden, A=0.7; and (e) Junipero Serra, A=0.4. The triangles are the measured data; the solid line is the calculated curve fit. The value of the constant of proportionality, A, was estimated by fitting the function f(z) = A sec(z) to the measured data.

As can be seen from figure 3, the parameter A varies as a function of city. It was assumed that A is itself a function of population. The estimates of A for the population defined previously in table 1 are shown in table 2.

Table 2. Estimates of the constant of proportionality, A, and the corresponding population inferred from the series of plots shown in figure 3, plots (a) through (e).

log P	Constant of Proportionality, A
3.0	0.4
3.5	0.7
4.0	0.9
4.5	1.2
5.0	1.6
5.5	2.0
6.0	2.4
6.5	2.9

Due to the nature of the secant function (it goes to infinity for angles approaching 90°), Berry suggests using this function only up to 80°. For the range 80–100°, the value of the secant law valid at 80° is used. Beyond 110°, a modified secant law is used; the modification is comprised of subtracting one to ensure that the value of the zenith angle correction approaches zero as the zenith angle approaches 180°. Between 100° and 110°, the value is determined through interpolation. In summary, the zenith angle correction function is computed as

$0 < z <= 80$	$f(z) = A(P) \sec(z)$,
$80 < z <= 100$	$f(z) = A(P) \sec(80)$,
$100 < z <= 110$	$weight = (z-100) / 10$
	$f(z) = A(P) ((1-weight) \sec(80) + weight (\lvert\sec(z)\rvert - 1))$,
$110 < z <= 180$	$f(z) = A(P) (ABS(\sec(z)) - 1)$.

A graph of this function as a function of zenith angle is shown in figure 4, where a value of one for the constant of proportionality, A, has been assumed.

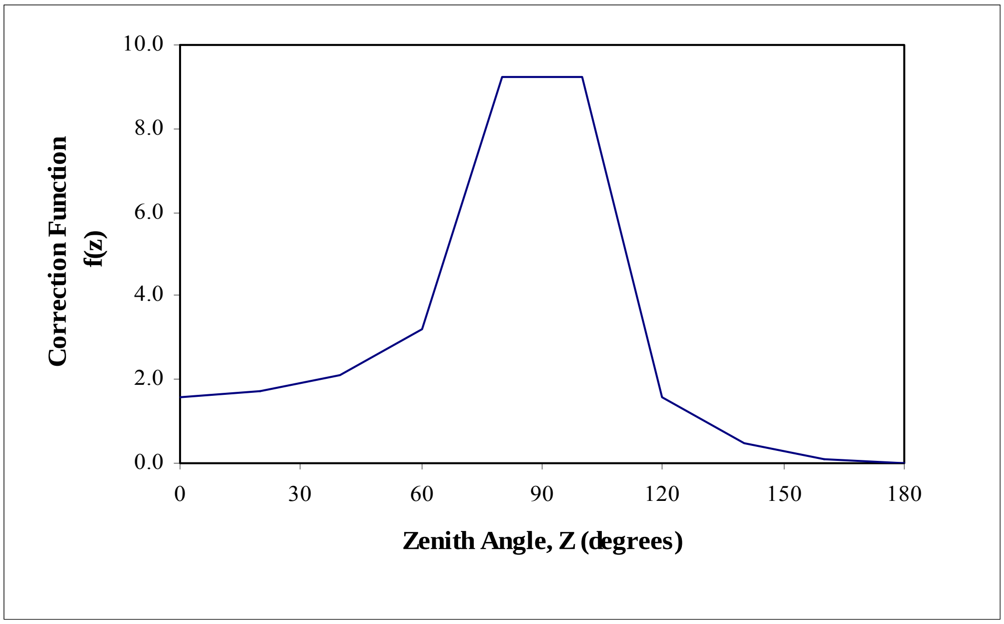

Figure 4. Zenith angle correction function, f(z).

3.1.3 Azimuth-Angle Effects

A literature review did not produce any models for the azimuthal variations in urban brightness levels. However, experience tells us that the light from a city drops off very rapidly as you look away from the city to the left or right. Therefore, a Gaussian weighting function was employed it, because it has several advantageous characteristics: it has a magnitude of one at $\beta = 0$, it drops off as slowly or rapidly as required based on the value of the variance of the distribution, it

drops approximately to zero weight for azimuth angles in the tail of the distribution, and it is symmetric for positive and negative azimuth angles. Using a Gaussian model to correct the brightness predicted by the brightness-distance relationship for variations in azimuth angle, an azimuth angle function was defined as follows:

$$f(\beta) = e^{\left(\frac{-\beta^2}{2 \times factor \times sigma^2}\right)}, \tag{3}$$

where β is the azimuth angle ($\beta = 0°$ when looking directly at the city, $\beta = \pm 180°$ when looking directly away from the city), $sigma^2$ is the variance of the distribution that defines the width of the Gaussian weighting function, and *factor* is a multiplicative factor used to modify the standard variance.

Based on qualitative observations, the variance of the Gaussian weighting function as a function of zenith angle was modified. By multiplying the variance by a variable "factor," a new effective variance is produced. This factor was set equal to sec(90°-z), resulting in a larger effective variance for small zenith angles and decreasing as the zenith angle approaches 90°. This ensures that the azimuthal dependence of the sky brightness decreases as one looks toward the zenith.

A value for the variance that results in a 50% decrease in brightness over a 30° (0.5236 radians) range at a zenith angle of 90° was selected. To calculate $sigma^2$:

$$0.5 = e^{\left(\frac{-0.5236^2}{2 \times factor \times sigma^2}\right)}, \tag{4}$$

$$sigma^2 = \frac{-0.5236^2}{2 \times \ln(0.5)}, \tag{5}$$

$$sigma^2 = 0.19776 \text{ rad}^2. \tag{6}$$

In summary, the azimuth angle correction function is computed in two steps. First, determine the value for the factor used to modify the variance:

0 < z <= 90	factor = 1.0 / cos(90 - z),
90 < z <= 180	factor = 1.0.

Then, calculate the function itself:

$$f(\beta) = e^{\left(\frac{-\beta^2}{2 \times factor \times sigma^2}\right)}. \tag{7}$$

A graph of the azimuth angle correction function for three sample zenith angles is shown in figure 5.

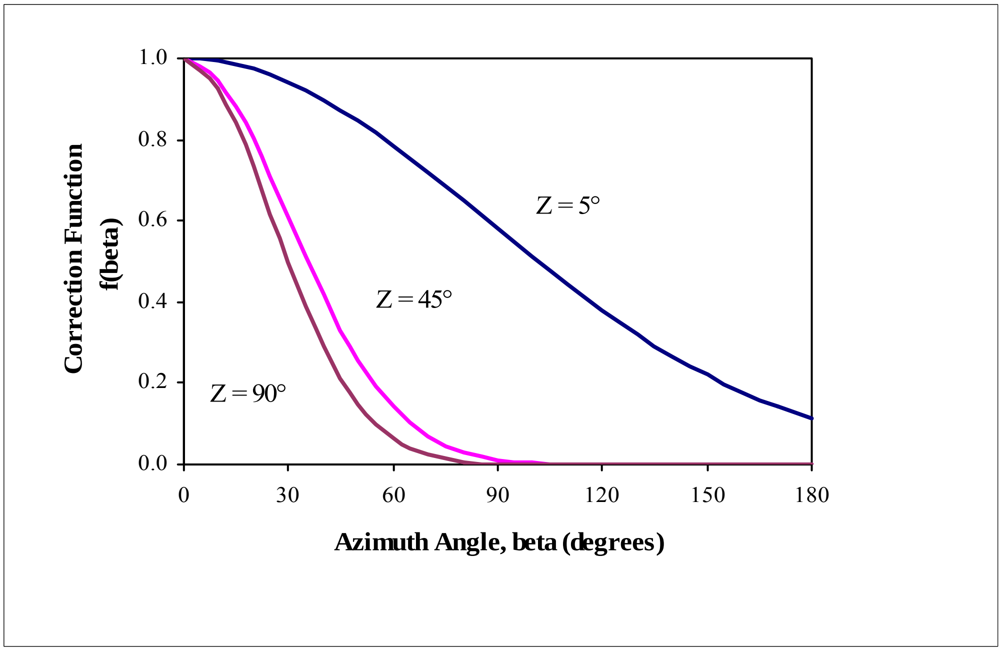

Figure 5. Azimuth angle correction function, f(β), for three sample zenith angles (z=5°, 45°, and 90°).

After identifying the correction factors for the change in brightness due to zenith and azimuth angle effects, the broadband brightness from the city is calculated by combining equations 1, 3, and 7

$$B = CPD^{-\alpha}\ f(z)\ f(\beta) \tag{8}$$

3.2 Clouds

3.2.1 Properties

A limited ability to examine reflection of city lights from an overcast cloud deck has been included. Altostratus/altocumulus (As/Ac), cumulus/cumulonimbus (Cu/Cb), and stratocumulus/stratus (Sc/St) cloud types are available for selection. Table 3 presents the cloud base heights, taken from Low (*13*), and cloud reflectivities as a function of reflection angle, taken from Shapiro (*14*).

Table 3. Reflectivities (ρ) for various cloud types as a function of cosine zenith angle (Z).

Cloud Type \ ρ	Cos Z 0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95
As/Ac	.650	.645	.621	.604	.587	.576	.569	.562	.560	.560
Sc/St	.661	.650	.636	.611	.592	.575	.561	.549	.535	.520
Cu/Cb	.703	.693	.676	.660	.648	.639	.629	.620	.613	.609

3.2.2 Methodology

The brightness reflected from the cloud layer was calculated under a non-scattering atmosphere with an extinction coefficient of .15 km^{-1}, or a visibility of approximately 25 km. The total light output from the city is LP lumens, were P is the population and L is the lumens per head of the population. A value of L = 1000 was taken for the value of lumens per head of the population (*7*). No provision was made for shielding of the luminaries. Simple attenuation is carried out over the two paths considered: directly upward from the city and along the observer's LOS. The brightness was further modified using the previous correction factors for falloff in both the zenith and azimuthal directions. The resulting equation is

$$B = \frac{LP}{4\pi^2 h^2} f(z) f(\beta) \rho(z) e^{-\tau_1} e^{-\tau_2}, \tag{9}$$

where h is the height of the cloud deck, ρ is the cloud and angle dependent reflectivity, and the optical depths along the paths considered are τ_1 = k h, and τ_2 = k r, where k is the extinction coefficient and r is the slant path distance between the cloud base and observer.

4. Spectral Composition of the Broadband Brightness

Next, the spectral composition of urban light must be determined. This is done by identifying the types of lights used in typical cities and estimating the percentage that each light source contributes to the overall city lights. Finally, the spectral radiance values over the sensor's waveband are calculated based on the brightness amount due to each individual light source. The method for accomplishing this is discussed below.

4.1 Light Types

The types of lights that comprise urban setting, and their spectral content, must be known for the model to function, i.e., an illumination database of some nature is required. In any given city many light types are employed on city streets, highways, office buildings, shopping centers, stadiums, houses, parking lots, etc. The resulting mix of light is highly heterogeneous due to the variety of light source spectra and the effects that atmospheric scattering and absorption and reflection from the ground and scattering have on the light spectra. The mix contains both a broad continuum of radiation along with many superimposed emission lines at specific wavelengths. From 300–500 nm, a pseudo continuum is formed by the many emission lines of the mercury vapor and multivapor lights (*15*). Beyond 500 nm, incandescent and high pressure sodium lamps are the primary contributors to the city light continuum.

In this model, a given mix of light sources was assumed and the proportion of light that is provided by each type was estimated from lighting data taken for Santa Clara County in northern California (*16*), broken down into individual light types by percent. The results are presented in table 3.

Table 3. Breakdown of streetlights in Santa Clara County, CA (*16*).

Light Type	Percent of Total Light
Color corrected mercury	67.1
Clear mercury	20.7
Incandescent	7.0
High pressure sodium	4.2
Low pressure sodium	0.3
Other	0.7
Total	100

Using these lighting percentages, the amount of the brightness due to each light type was determined by multiplying the broadband brightness by each percentage. For example, $B_{\text{high pressure sodium}} = B \times 0.042$ and $B_{\text{clear mercury}} = B \times 0.207$, where $B_{\text{high pressure sodium}}$ is the brightness due to high pressure sodium lights and $B_{\text{clear mercury}}$ is the brightness due to clear mercury vapor lights.

Each of the six light types listed in table 3 has a characteristic spectral distribution. A warm white fluorescent light type was assumed for the category listed as “other” in the table. Spectral distributions (covering a range of wavelengths from 300 to 700 nm) for these light types (*15*) were used along with general knowledge of each light’s emission lines and continuum to build light spectra for the range 300–1100 nm at 10 nm resolution. These distributions were digitized for each of the six light types and coded into the model.

4.2 Radiant Energy Determination

The total radiant energy (in relative units) for each light type was computed by summing the area under the spectrum over the entire wavelength range (300–1100 nm). The total radiant energy, E, for a specific light type (specified by the index i) is thus given by

$$E_i = \sum_{\lambda=300}^{\lambda=1100} e_{i\lambda} \ , \tag{10}$$

where $e_{i\lambda}$ is the radiant energy at a specific wavelength taken from the digitized spectra. This quantity is precomputed for use in the code. The radiant energy (in relative units) corresponding to a specific wavelength band (specified by the index λ) is computed similarly, where the sum is over the sensor wavelengths of interest, defined by $\lambda_{\min}$ and $\lambda_{\max}$:

$$E_{i\lambda} = \sum_{\lambda_{\min}}^{\lambda_{\max}} e_{i\lambda} \ . \tag{11}$$

Finally, the broadband brightness can be broken into its spectral components by summing the contributions from each of the light types to each spectral band. The total brightness in a wavelength band defined by $\lambda_{\min}$ and $\lambda_{\max}$ is calculated as follows:

$$\mathrm{B}_{\lambda} = \sum_{i=1}^{i=6} \left(\frac{E_{i\lambda}}{E_i}\right) \mathrm{B}_i \ . \tag{12}$$

where B_i is the proportion of the broadband brightness associated with a specific light type.

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5. Convert Brightness to Radiance Units

The final step in calculating the contribution to radiance due to urban illumination is to convert from nL to watt/m^2/sterad/micron. In this case, we first converted to nL/micron by normalizing the spectral radiance value computed above by the width of the wavelength interval in microns. Equation 13 was used for the final conversion:

$$\text{B (watt/m}^2\text{/sterad/micron)} = \text{B (nL/micron)} * 1.457\times 10^7 . \tag{13}$$

6. Validation

The model was compared to an equivalent formulation by Albers (*17*). Since his model is only valid for the brightness at the zenith, comparisons were made for a zenith and azimuthal angles of zero, with no correction factors considered, i.e., f(z), f(beta). The results of the two models agreed to a factor less than 2. The model will be further validated at a future date.

7. Conclusion

This model builds on previous research that predicts the broadband brightness as a function of population and distance from the city center. To that distance-based model azimuth and zenith dependencies were added to predict changes to the brightness for off-angle viewing directions. Finally, a sample region was used as a model for the types of light sources employed in urban lighting. These data define the spectral composition of the broadband illumination.

This model is simple and fast. Several caveats concerning the model are compiled here. A more detailed model will examine these issues in the future.

The current model caveats are as follows:

- A broadband brightness model was developed for visual waveband and is assumed to hold true for near-infrared too.
- Model parameters were selected for a single atmospheric state.
- Cities are treated as point sources.
- Target is located relatively far from the city center and at a relatively low altitude ($D >> h$).
- Lighting definition is built from only one sample city.
- Lighting data are dated.

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Acronyms and Abbreviations

As	altostratus
Ac	altocumulus
ARL	U.S. Army Research Laboratory
Cb	cumulonimbus
Cu	cumulus
DMSP	Defense Meteorological Satellite Program
IWARS	Infantry Warrior Simulation
LOS	line-of-sight
MODTRAN	Moderate Transmission
NVGs	night vision goggles
Sc	stratocumulus
St	stratus
TAWS	Target Acquisition Weapons Software

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